A single analytical model for sparkle and graininess patterns in texture of effect coatings

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Abstract: Flakes in effect coatings, which are responsible for its color shift, are not perfectly horizontally oriented, producing a non uniform texture when observed from a distance of around one meter or less. If the coating is illuminated by a diffuse source, a granular appearance is observed, called graininess. But when the coating is illuminated by unidirectional light, some luminous spots on a dark background appear, effect that is known as sparkle. The characterization of these two textures is getting more important for automotive industry because of the high percentage of cars with effect coatings and because improvements in imaging technology allows this effect to be measured by, for instance, commercial instruments as BYK-mac. A single analytical model to understand and radiometrically characterize both sparkle and graininess in effect coatings is presented and studied in this work. It allows both patterns to be explained and, despite its simplicity, includes variables related to the optical system (Point Spread Function (PSF) and size of the entrance pupil), its distance to the coating, the diffusion grade of the illumination, the illumination and observation directions, and coating parameters.

OCIS codes: (120.5700) Reflection, (240.6700) Surfaces.

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1. Introduction

Effect and special effect coatings [1] present eye-catching color changes at different illumination and observation geometries. Due to their appealing appearance, they have become very popular in the automotive industry [2] and in other markets, such as the cosmetics industry or, for a more functional purpose, currency (anti-counterfeit measures).

This kind of coating consists of a transparent substrate having embedded metallic or interference pigments that are horizontally arranged [3]. The flakes, which are responsible for the observed color shift, are not perfectly oriented within a horizontal plane, contributing to the non uniform texture when observed from a distance of around one meter or less. The characterization of this non uniform texture is getting more important for automotive industry because of the high percentage of cars with effect coatings[4] and because improvements in imaging technology allows this effect to be measured by, for instance, commercial instruments as BYK-mac[5]. A typical problem is, for instance, matching the appearance of the repaired part of a car after an accident.

The non uniform texture of effect coatings is usually described as the composition of two distinctly separated perceptions: sparkle (or glint) and graininess (or diffuse coarseness) [5]. The former refers to the star-like appearance of luminous points on a dark background, and it is observed under the extreme condition of very directional illumination. On the other hand, graininess refers to the granular appearance that it is seen under other extreme condition, that is, under diffuse illumination. When any of these conditions is not completely fulfilled an intermediate texture is observed. These both extreme patterns are very different and only separated phenomenological models to characterize them have been proposed so far in the literature [6, 7], although the physical origin of both sparkle and graininess are obviously the reflection and transmission characteristics of flakes. Physical- and statistical-based Ershov's model [8] allows sparkle to be simulated, but it is too complex to be used for sparkle characterization and it does not consider graininess.

An analytical approach is presented in this work, where a single analytical model to understand and radiometrically characterize both sparkle and graininess in effect coatings is presented and studied in this work. It allows both patterns to be explained and, despite its simplicity, includes variables related to the optical system (Point Spread Function (PSF) and size of the entrance pupil), its distance to the coating, the diffusion grade of the illumination, the illumination and observation directions, and coating parameters. The latter variables will describe the coatings in potential sparkle/graininess terms, but the grade of sparkle/graininess at specific observation conditions is mainly determined by the illumination/observation parameters. A model with these characteristics is necessary as a starting point to completely identify the sparkle/graininess properties of a coating for any illumination/observation geometry.

2. Description of the model

The proposed model is based in the hypothesis that the bright spots in sparkle patterns and the grains in graininess patterns are both produced by the luminous flux specularly reflected in flakes. Since these flakes are not perfectly horizontally arranged in the bulk, the proportion of this luminous flux collected by the entrance pupil varies depending on the flake, giving rise to the intensity variation on the image plane.

The value of the collected luminous flux from a single flake can be calculated considering the geometrical and radiometric variables represented in Fig. 1.

The coating is illuminated by a source S of radius R_S at a distance d_S and from a direction given by the spherical coordinates (ϑ_S,φ_S) or by the unit vector $\mathbf{r}_S$ respect to the reference system, defined by its normal unit vector $\mathbf{N}$. The higher the ratio R_S/d_S the more diffuse is the illumination on the surface. Reciprocally, the observer O is located at a distance d_O, the

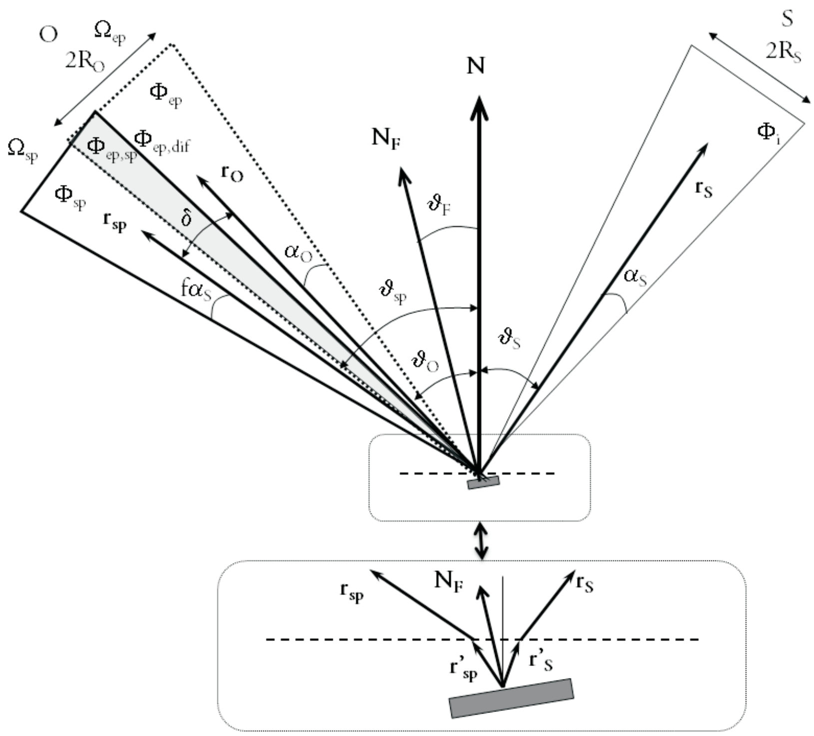

Fig. 1. Geometrical and radiometric variables involved in the calculation of the collected luminous flux from a single flake.

radius of its entrance pupil is R_O and its direction is (ϑ_O,φ_O) or $\mathbf{r}_O$. The half-angles of the solid angle of illumination and observation (α_S and α_O, respectively) are calculated from the corresponding radius and distances. The orientation of a given flake inside the coating is given by (ϑ_F,φ_F) or by its normal unit vector $\mathbf{N}_F$. It is assumed that the size of the flake is very small respect to the dimensions of the illumination and observation geometries.

The luminous flux collected by the entrance pupil (Φ_{ep}) (confined within the cone Ω_{ep}) is composed by two different fluxes: The luminous flux specularly reflected by the flake ($\Phi_{ep,sp}$) and the luminous flux directed to the entrance pupil from other reflection mechanisms ($\Phi_{ep,dif}$), for instance, diffuse light from the bulk, specular reflection on the clear coat or light from several reflections between metallic or interference pigments.

The luminous flux specularly reflected by the flake (Φ_{sp}) is proportional to the incident luminous flux Φ_i for a given illumination/observation geometry. The proportional constant, hereafter called ρ_{sp}, is wavelength dependent and includes Fresnel coefficients, absorption through the bulk and size of the flake.

Φ_{sp} is confined within a cone Ω_{sp} centered around the specular direction of the flake, with a half-angle α_{sp} close to α_S, lying the slight difference in the fact that the flake is not completely flat. Therefore, a parameter denoted flatness (f) is added to the model, whose effect is equivalent to modify α_S (the directionality of the illumination):

$$\alpha_{sp} = f\alpha_S \tag{1}$$

The proportion of Φ_{sp} arriving to the entrance pupil of the observer $\Phi_{ep,sp}$ depends on the

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angular distance δ between the direction of Φ_{sp} ($\mathbf{r}_{\mathrm{sp}}$) and the observation direction $\mathbf{r}_{\mathrm{O}}$. It is calculated from the unit vector $\mathbf{r}_{\mathrm{O}}$ and the unit vector $\mathbf{r}_{\mathrm{sp}}$:

$$\cos\delta = \mathbf{r}_{\mathrm{O}} \cdot \mathbf{r}_{\mathrm{sp}} \tag{2}$$

where $\mathbf{r}_{\mathrm{sp}}$ is derived, by previously calculating $\mathbf{r}'_{\mathrm{sp}}$ from the relation:

$$\mathbf{r}'_{\mathrm{S}} + \mathbf{r}'_{\mathrm{sp}} = (2\mathbf{N}_{\mathrm{F}} \cdot \mathbf{r}'_{\mathrm{S}})\mathbf{N}_{\mathrm{F}} \tag{3}$$

where $\mathbf{r}'_{\mathrm{S}}$ represent the direction of the illumination from the flake position (within a medium of refractive index n) and, in the same way $\mathbf{r}'_{\mathrm{sp}}$ represent the direction $\mathbf{r}_{\mathrm{sp}}$ from the flake position (see Figure 1). The transformation from $\mathbf{r}_{\mathrm{S}}$ to $\mathbf{r}'_{\mathrm{S}}$ is accomplished by transforming the polar spherical coordinate according to Snell' law:

$$\vartheta'_{\mathrm{S}} = \arcsin\left(\frac{\sin\vartheta_{\mathrm{S}}}{n}\right) \tag{4}$$

and similarly to transform from $\mathbf{r}'_{\mathrm{sp}}$ to $\mathbf{r}_{\mathrm{sp}}$:

$$\vartheta_{\mathrm{sp}} = \arcsin\left(n\sin\vartheta'_{\mathrm{sp}}\right) \tag{5}$$

$\Phi_{\mathrm{ep,sp}}$ is proportional to the area of intersection I between the circular section of the cone Ω_{ep} and the circular section of the cone Ω_{sp}. This area was accounted as the intersection of two circles of radii $f\alpha_{\mathrm{S}}$ and α_{O} separated a distance δ. This intersection can be calculated using the formula for the area A_{cs} of the circular segment of radius R and chord-center distance h:

$$A_{\mathrm{cs}}(R,h) = R^2 \arccos\frac{|\,h\,|}{R} - |\,h\,|\sqrt{R^2-h^2} \tag{6}$$

Given two circles 1 and 2 with radii R_1 and R_2 with centers located at (0,0) and (0,D), their respective h_1 and h_2 are deduced as:

$$h_1 = \frac{D}{2} + \frac{R_1^2-R_2^2}{2D}; \qquad h_2 = \frac{D}{2} - \frac{R_1^2-R_2^2}{2D} \tag{7}$$

If $R_1 > R_2$ and the circumferences of both circles intersect, the intersection of these two circles is:

$$I(R_1,R_2,D) = \begin{cases} \frac{1}{\pi R_2^2}\left[A_{\mathrm{cs}}(R_1,h_1) + A_{\mathrm{cs}}(R_2,h_2)\right] & \text{if } h_2 \geq 0 \\ \frac{1}{\pi R_2^2}\left[A_{\mathrm{cs}}(R_1,h_1) + \pi R_2^2 - A_{\mathrm{cs}}(R_2,h_2)\right] & \text{otherwise} \end{cases} \tag{8}$$

where I is normalized to have the unit as maximum.

A similar calculation can be done if the source is not circular but rectangular.

Bearing in mind these expressions, it can be written for the proposed model:

$$\Phi_{\mathrm{ep,sp}} = \begin{cases} I(f\alpha_{\mathrm{S}},\alpha_{\mathrm{O}},\delta)\Phi_{\mathrm{sp}} & \text{if } f\alpha_{\mathrm{S}} \geq \alpha_{\mathrm{O}} \\ I(\alpha_{\mathrm{O}},f\alpha_{\mathrm{S}},\delta)\Phi_{\mathrm{sp}} & \text{otherwise} \end{cases} \tag{9}$$

Similarly to $\Phi_{\mathrm{ep,sp}}$, $\Phi_{\mathrm{ep,dif}}$ is proportional to the incident luminous flux Φ_{i}. The proportionality constant is denoted as ρ_{dif}, which is wavelength and illumination/observation geometries

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dependent and is proportional to the entrance pupil solid angle. It is closely related to the spectral Bidirectional Reflectance Distribution Function (BRDF)[9] of the coating, which, unlike sparkle and graininess, is a far-field property.

Therefore, the total luminous flux collected by the entrance pupil from the direction of a single flake can be written as:

$$\Phi_{\mathrm{ep}} = \Phi_{\mathrm{ep,dif}} + \Phi_{\mathrm{ep,sp}} = \Phi_{\mathrm{i}}[\rho_{\mathrm{dif}} + \rho_{\mathrm{sp}} I(f\alpha_{\mathrm{S}}, \alpha_{\mathrm{O}}, \delta)] \tag{10}$$

3. Rendering texture images

The texture can be rendered by calculating Φ_{ep} at different positions of the focal plane of the receptor, assuming a certain orientation distribution of the flakes. In addition, the Point Spread Function (PSF) of the eye can be applied to resemble the diffraction-limited effect of its optical system. A nonlinearity or a saturation function can be used to resemble the acquisition by a camera with saturation at some extent.

Application of Eq. (10) is shown in Fig. 2. The resolution of these images is 500 pixels $\times$ 1000 pixels. Since the model for the collected flux from a flake is applied for every pixel, the scale of the image is as one pixel representing one flake. This way, for instance, for an average size of flake of 50 μm, the image size is 2.5 cm $\times$ 5 cm. This is only an idealization, since flakes are not equally separated each other. We assume that this simplification does not change in great extent the texture effect. The rendering time for one image is around 0.9 s, operated by Matlab in a conventional workstation (2.6 GHz).

It was assumed that both observer and illumination are far away enough to consider that all flakes in the image are observed and illuminated at approximately the same angles, allowing these angles to be taken as constants. A slightly more complex way of modeling these images is required if this assumption is not valid.

The orientation distribution of the flakes is taken as Gaussian for the angle of their surfaces and the horizontal (ϑ_{F}) (with a standard deviation of σ_{F}) and uniform regarding azimuthal orientation (φ_{F}).

Images shown in Fig. 2 were created using the following fixed values: $\vartheta_{\mathrm{S}} = 20^{\mathrm{o}}$, $\varphi_{\mathrm{S}} = 0^{\mathrm{o}}$, $\vartheta_{\mathrm{O}} = 25^{\mathrm{o}}$, $\varphi_{\mathrm{O}} = 180^{\mathrm{o}}$, $R_{\mathrm{O}}/d_{\mathrm{O}} = 5 \times 10^{-3}$, $\sigma_{\mathrm{F}} = 7^{\mathrm{o}}$, $\rho_{\mathrm{sp}}/\rho_{\mathrm{dif}} = 50$, $n = 1.5$ and $f = 1$. The value of α_{S} is doubled for every image, from top-left to bottom-right, from 0.11^{o} to 14.4^{o} (values shown on the top of each image). The calculated images were convolved with a Gaussian PSF with a standard deviation of 8 pixels (0.4 mm). It is clearly observed the transition from sparkle texture to graininess texture when α_{S} is increased (from very directional to less directional illumination), according to the appearance of effect coatings.

4. Discussion

The presented model explains sparkle and graininess as two extremes of the same reflection phenomenon. If the sparkle spots are clearly distinguishable in a specific observation condition, the sparkle texture is observed, whereas if they are not, graininess can be perceived, but not always. Two conditions have to be fulfilled to clearly distinguish sparkle spots. First, a meaningful proportion of them has to be resolvable, that is, the mean distance between them must be at least similar to their apparent size in the image, defined by the PSF. Second, contrast C between sparkle spots and background has to be high enough. We defined this contrast as the increase of luminous flux produced by a very bright sparkle spot ($\Phi_{\mathrm{ep,sp}}$) respect to a constant level or background ($\Phi_{\mathrm{ep,dif}}$):

$$C = \frac{max(\Phi_{\mathrm{ep}}) - \Phi_{\mathrm{ep,dif}}}{\Phi_{\mathrm{ep,dif}}} = \frac{max(\Phi_{\mathrm{ep,sp}})}{\Phi_{\mathrm{ep,dif}}} = \frac{\rho_{\mathrm{sp}}}{\rho_{\mathrm{dif}}} \tag{11}$$

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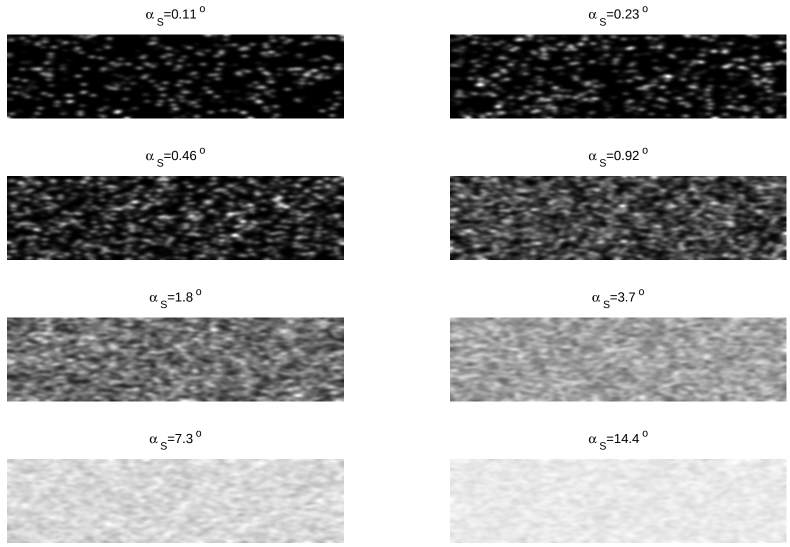

Fig. 2. Sparkle/graininess patterns as a result of applying Eq. (10) to a surface with flakes oriented at different directions. α_S increases from top-left to bottom-right, whereas the other variables are kept constant.

Contrast C depends on illumination/observation geometry and on the wavelength via ρ_{sp} and ρ_{dif}.

Proper contrast allows the texture to be observed, but the density of sparkle spots determines whether it appears as sparkle or graininess. Graininess is perceived when this density is high and the resolvability condition is not completely fulfilled, whereas sparkle corresponds to the case of low density of sparkle spots.

The density of sparkle spots in the image depends on the illumination/observation geometry, and on the parameters and orientation distribution of the flakes. The more flakes directing specular reflection on the flake in the entrance pupil, the more sparkle spots, which is favored with a wide distribution of illumination and observation directions (higher α_S and α_O). As a matter of fact, illumination and observation solid angles are exchangeable in their effects, and the smaller one limits the sparkle effect due to the variation of the other. The closer the observation direction to the specular direction, the higher the density of sparkle spots too, as long as the average of the orientation distribution of the flakes is parallel to the coating's normal.

When the illumination solid angle is higher than the entrance pupil solid angle, the density of sparkle spots for a given geometry can be formally defined as the probability that the luminous flux specularly reflected by any flake was partially or completely collected by the entrance pupil. Using the proposed model it is possible to calculate it for any condition in percentage units by counting the pixels with $\Phi_{ep,sp} > 0$. The density of sparkle spots was calculated by the model and plotted in Fig. 3 for values of α_S between 0^o and 30^o, and using the values quoted in section 3 for the other variables. It increases toward less directional illumination, as expected. Notice that the image corresponding to $\alpha_S = 3.7^o$ in Fig. 2, with graininess texture, has a density of sparkle spots of less than 10 %.

Density of the sparkle spots depends on the dispersion of the flakes orientation σ_F and on

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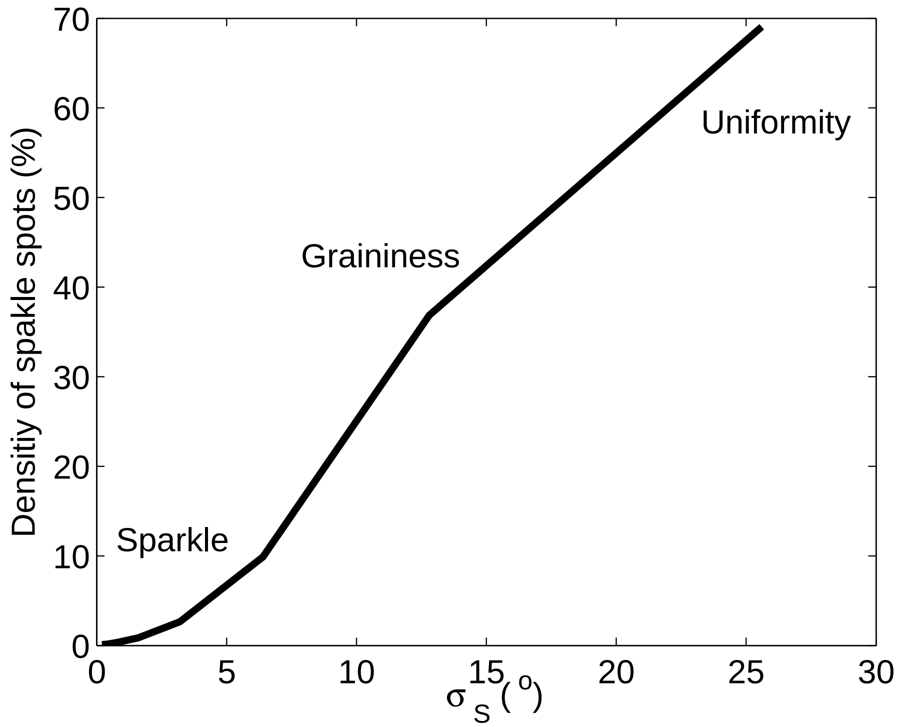

Fig. 3. Density of sparkle spots calculated by the model for values of α_S between 0^o and 30^o.

the flatness factor f in two different ways. The larger σ_F, the higher the probability that light from some flake arrives to a given point of the observation plane outside the specular direction, whereas the larger f, the higher the probability that light on some point of the image plane comes from a given flake, and this effect is exactly the same effect which occurs when $\alpha_S$is increased. In more explicit terms, the larger σ_F, the higher the density of sparkle spots outside the specular direction. The higher f or α_S, the higher the density of sparkle spots too, but, unlike the previous case, it has a cost in terms of energy per spot and contrast.

5. Conclusions

A single analytical model to explain both sparkle and graininess texture in effect coatings is presented in this work. This very simple model is based on the hypothesis that the bright spots in sparkle pattern and the grains in graininess pattern are both produced by the different amount of luminous flux specularly reflected by the flakes collected by the pupil entrance of the observer. It includes variables related to the optical system (Point Spread Function (PSF) and size of the entrance pupil), its distance to the coating, the diffusion grade of the illumination, the illumination and observation directions, and coating parameters.

We conclude that just two variables have to be studied at different illumination/observation geometries to establish the sparkle/graininess characteristic of a specific coating: contrast and density of sparkle spots. The former variable is determined by the specular reflectance of the flakes, by their size and by the diffuse reflectance of the coating, which is very closely related to the BRDF. The latter variable is determined by the orientation distribution of the flakes and

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by their flatness.

Despite its simplicity, this model includes the essential concepts and parameters to understand sparkle/graininess of effect coatings and should be very helpful for its radiometric characterization and for the design of sparkle/graininess psychophysics experiments.

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